

# Radiation balance and evaporation partitioning in a narrow-row soybean canopy

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## Abstract

Seeding rate and row spacing of agricultural crops are managed to maximize yield but also have significant implications for energy partitioning and canopy microclimate. The objective of this study was to measure radiation budget components in a narrow-row soybean [*Glycine max* (L.) Merr.] canopy, determine soil water evaporation ( $E$ ) as the difference between measured evapotranspiration (ET) and plant transpiration ( $T$ ), and compare measured  $E$  and  $T$  with estimates from an energy balance approach. The study was completed in a production soybean field near Ames, IA, with 350,000 plants  $\text{ha}^{-1}$  in 0.38 m wide rows. The field was planted on 8 May 2004 and continuous measurements were made from 8 June to 27 September. Shortwave and longwave radiation components were measured above the canopy with hemispherical radiometers. Net all-wave and incoming and reflected shortwave radiation were measured beneath the canopy with line radiometers and downwelling longwave radiation was calculated from a radiation balance. ET was measured with an eddy covariance system and  $T$  was measured with sapflow stem gauges. On sunny days under full canopy conditions, nearly 90% of the shortwave and net radiation was attenuated by the canopy with over 80% of the available energy utilized by ET.  $E$  accounted for 8–12% of the ET under full canopy conditions although these percentages may be overestimates due to evaporation of dew present on the canopy. With such a large proportion of the available energy consumed by ET, fluxes of sensible heat ( $H$ ) were very low and vertical temperature gradients across the soil–canopy–atmosphere interface were only 2–3 °C. A Priestley–Taylor energy balance approach used to estimate  $E$  and  $T$  tended to underestimate  $E$  and overestimate  $T$ . The  $E$  underestimate may be due in part to  $E$  including evaporation of dew. Conversely,  $T$  was overestimated by 25 and 14% on sunny days under full canopy conditions even with direct measurement of  $R_n$  interception by the canopy. Use of shortwave extinction coefficients to estimate  $R_n$  interception failed to improve  $T$  estimates significantly. The high-population, narrow-row planting strategy resulted in a dense canopy that, under full canopy conditions, resulted in very little light penetration or  $E$ .

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## 1. Introduction

The radiation balance of plant canopies is an intricate interplay between absorption, reflectance, and trans-

mission of energy by vegetation and soil over a range of wavelengths from the ultraviolet to infrared. Growth habit of the plants, plant density, and surface soil properties all influence the radiant energy regime of agricultural crops. Radiation interception by the crop canopy affects all components of canopy microclimate including the partitioning of evapotranspiration (ET) between evaporation directly from the soil ( $E$ ) and

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transpiration from the plant ( $T$ ). Cultural practices from row spacing and seeding rate to variety selection strongly influence the local microclimate created by the plant canopy.

Soybean [*Glycine max* (L.) Merr.] is a major crop in the Midwestern U.S. with over 30 mill. ha under cultivation in the U.S. in 2006 (National Agricultural Statistics Service, 2006). Soybean row spacing and/or plant population effects on light interception, yield, and canopy characteristics have been the subjects of study since the 1960s (Shibles and Weber, 1966; Weber et al., 1966; Singh et al., 1968). Recent soybean production practices have trended toward narrower row spacing (0.18–0.38 m) and greater plant population ( $\sim 400,000 \text{ ha}^{-1}$ ) with the goal of maximizing light interception and crop yield (Board et al., 1990; Wells, 1991; Edwards et al., 2005). It is uncertain what effect such dense soybean canopies may have on energy partitioning and canopy microclimate.

Baldocchi et al. (1983) reported net radiation ( $R_n$ ) was attenuated exponentially with depth in the canopy for two soybean varieties planted in 0.75 m rows near Mead, NE. Under full canopy conditions, attenuation of  $R_n$  was independent of solar elevation and was greater for a planophile variety than an erectophile. Ham and Kluitenberg (1993) found significant spatial patterns of  $R_n$ , soil heat flux ( $G$ ), and soil surface temperature ( $T_{\text{soil}}$ ) associated with solar irradiance beneath a wide-row (1 m) soybean canopy with partial cover near Manhattan, KS. Brun et al. (1972) estimated  $E$  beneath a soybean canopy in Kansas with 330,000 plants  $\text{ha}^{-1}$  at 0.6 m row spacing to be 25% of ET over the interval from 1 week after planting until maturity. Soil water evaporation was estimated to be equivalent to the below-canopy available energy ( $R_n - G$ ). Sakuratani (1987) calculated  $E$  beneath a soybean canopy in Japan with 62,500 plants  $\text{ha}^{-1}$  at 0.4 m row spacing as the difference between ET and  $T$  measured with Bowen ratio and stem flow gauges, respectively. Over the growing season, ET varied from 2 to 6 mm  $\text{day}^{-1}$  with  $E$  decreasing from 80% under partial canopy to 10% at full canopy.

Ritchie (1972) introduced the energy balance approach to estimate  $E$  and  $T$  separately for a canopy with incomplete cover. Tanner and Jury (1976) utilized forms of the Priestley–Taylor (1972) equation to obtain separate estimates of  $E$  and  $T$  based on the amount of  $R_n - G$  above and below a potato (*Solanum tuberosum* L.) canopy. This same approach was used by Morgan et al. (2003) for a corn canopy (*Zea mays* L.) in Wisconsin. In each instance, under energy-limiting conditions, estimates of  $E$  beneath canopies were

estimated based on the amount of  $R_n - G$  at the soil surface. Previous studies on soybean have not included the simultaneous measurement of the  $R_n - G$  with  $E$  and  $T$  to assess the applicability of this energy balance approach. The objective of this study was to measure radiation budget components in a narrow-row soybean canopy, determine  $E$  as the difference between measured ET (eddy covariance) and  $T$  (sapflow stem gauges), and compare measured  $E$  and  $T$  with estimates from the energy balance approach.

## 2. Methods

The study was conducted during the 2004 growing season in a 31.5 ha production soybean field near Ames, IA (41°97'N, 93°69'W, 315 m a.s.l.). The field had been in a long-term corn (*Z. mays* L.)–soybean rotation with chisel plow tillage. Soils in the field include Clarion loam (fine-loamy, mixed, superactive, mesic Typic Hapludoll), Nicollet clay loam (fine-loamy, mixed, superactive, mesic Aquic Hapludolls), and Canisteo silty clay loam (fine-loamy, mixed, superactive, calcareous, mesic Typic Endoaquolls). The planophile soybean cultivar Pioneer<sup>1</sup> 92M70 was planted at 380,260 seeds  $\text{ha}^{-1}$  on 8 May 2004 (day 129) in 0.38 m wide north–south rows. Stand density measured during vegetative and reproductive growth stages averaged 35 plants  $\text{m}^{-2}$ . Canopy height was measured manually with a ruler and a LAI-2000 Plant Canopy Analyzer (LI-COR Biosciences, Inc., Lincoln, NE) was used to measure leaf area index (LAI) throughout the growing season. The LAI-2000 measurements were made at the soil surface and at 0.15 m above the soil (line sensor reference height). The field was harvested on 28 September (day 272).

### 2.1. Within-canopy measurements

Continuous within-canopy radiation measurements and microclimate characterization began on 8 June (day 160) in the center of a 7.5 m  $\times$  7.5 m area enclosed by wire mesh fencing. Shortwave transmission beneath the canopy ( $R_{s,\downarrow T}$ ) was measured with two tube solarimeters (TSL, Delta-T Devices Ltd., Burwell, Cambridge, UK) placed diagonally across separate interrows 0.15 m above the soil surface. Shortwave reflection from the soil surface beneath the canopy ( $R_{s,\uparrow T}$ ) was measured with two inverted tube solarimeters at the same height

<sup>1</sup> Mention of trade names or commercial products in this article is solely for the purpose of providing specific information and does not imply recommendation or endorsement by the U.S. Department of Agriculture.

placed diagonally across the same interrows. Longwave emission from the soil surface ( $R_{l,\uparrow T}$ ) was estimated using the Stephan–Boltzmann law

$$R_{l,\uparrow T} = \varepsilon \sigma T_{\text{soil}}^4 \quad (1)$$

where  $\varepsilon$  is the emissivity,  $\sigma$  the Stephan–Boltzmann constant ( $5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ ), and  $T_{\text{soil}}$  is the soil surface temperature (K) measured beneath the canopy with two infrared thermometers (IRTS-P, Apogee Instruments Inc., Logan, UT). The infrared thermometers were adjusted from 0.6 to 0.2 m above the soil as necessary to obtain an unobstructed field-of-view. Soil emissivity was assumed = 0.95. Net radiation 0.15 m above the soil surface ( $R_{n,T}$ ) was measured with a tube net radiometer (TRL, Delta-T Devices) placed diagonally across an interrow. Data collection with the tube net radiometer began on 27 July (day 209). After this date, downwelling longwave radiation beneath the canopy ( $R_{l,\downarrow T}$ ) was calculated as the residual of the canopy radiation balance.

$$R_{l,\downarrow T} = R_{n,T} - R_{s,\downarrow T} + R_{s,\uparrow T} + R_{l,\uparrow T} \quad (2)$$

A leaf wetness sensor (237, Campbell Scientific, Inc., Logan, UT) was placed within the canopy 0.15 m above the soil to determine when dew was present. Air temperature ( $T_a$ ) was measured with 0.079 mm diameter copper–constantan thermocouples inside solar radiation shields at heights of 0.15, 0.35, 0.65, and 1 m above the soil surface. A third infrared thermometer was positioned directly above a plant row to measure canopy temperature ( $T_{\text{can}}$ ). Height of this sensor was adjusted from 0.15 to 0.30 m above the canopy as the canopy developed. Soil heat flux at 0.06 m ( $G_{0.06}$ ) was measured with five soil heat flux plates (HFT1.1, Radiation and Energy Balance Systems, Seattle, WA) with two plates in rows and three plates in interrow positions. Soil temperature was measured adjacent to each heat flux plate at depths of 0.015 and 0.045 m with 0.051 mm diameter copper–constantan thermocouples. Soil heat flux at the soil surface ( $G_0$ ) was calculated from the  $G_{0.06}$  data corrected for heat storage in the 0–0.06 m layer using the 0.015 and 0.045 m soil temperature data and calculated soil volumetric heat capacity (Fuchs and Tanner, 1968; Sauer, 2002). Soil water content for the volumetric heat capacity was determined from four samples collected approximately every 3 days with each sample composed of five 0.06 m deep  $\times$  0.019 m diameter cores. The samples were dried at 105 °C for 24 h to determine gravimetric water content, which were converted to a volumetric basis

( $\theta$ ,  $\text{m}^3 \text{ m}^{-3}$ ) using soil bulk density values determined on 8 June and 11 August.

## 2.2. Above-canopy measurements

Incoming ( $R_{s,\downarrow}$ ) and reflected ( $R_{s,\uparrow}$ ) shortwave and downwelling ( $R_{l,\downarrow}$ ) and upwelling ( $R_{l,\uparrow}$ ) longwave radiation above the soybean canopy were measured with a four-component net radiometer (CNR 1, Kipp and Zonen, Delft, The Netherlands) 2 m above the soil. Incoming ( $R_{s,\downarrow \text{soil}}$ ) and reflected ( $R_{s,\uparrow \text{soil}}$ ) shortwave radiation over bare soil were measured with a pair of pyranometers (Precision Spectral Pyranometer, The Eppley Laboratory, Inc., Newport, RI) 0.65 m above the soil. Signals from these sensors were recorded every 10 s and 15 min averages were stored on dataloggers (21X, Campbell Scientific, Inc.).

A permanent eddy covariance flux station consisting of a 3-D sonic anemometer (CSAT, Campbell Scientific, Inc.), an open path  $\text{CO}_2/\text{H}_2\text{O}$  gas analyzer (LI-7500, LICOR Biosciences Inc.), and a net radiometer (Q7\_1, Radiation and Energy Balance Systems) was located adjacent to the radiation measurement site. The CSAT and LI-7500 and the Q7\_1 were positioned 1.6 and 2 m above the soil surface, respectively. All sensors were continuously logged on a Campbell Scientific CR5000 data logger (eddy covariance sensors at 20 Hz, net radiometer at 1 s) with an output interval of 15 min. Sensible ( $H$ ) and latent (LE) heat fluxes were corrected using the Webb–Pearman–Luening correction procedure (Webb et al., 1980). Placement of the eddy covariance instrumentation at 1.6 m reduced the footprint of the flux measurements for better representation of the area near the radiation and sapflow measurements. As the height was constant, this does mean that the footprint decreased as the canopy height increased. The proximity of the sensors to the canopy creates concern regarding frequency response as the contribution of smaller scale eddies near the surface is within the sonic separation distance and thus may not be completely detected (Savage et al., 1995). This did not appear to be a significant source of error as energy balance closure values were near 85% under full canopy conditions. Thus, no frequency response or any of the other corrections that can be completed on eddy covariance flux data were applied (Massman and Lee, 2002; Ham and Heilman, 2003). The energy balance was closed by allocating unaccounted-for energy of the surface energy balance between LE and  $H$  using the Bowen ratio ( $H/\text{LE}$ ) as described by Twine et al. (2000). This approach assumes that  $R_n$  and  $G_0$  were measured accurately and that  $H$  and LE were both underestimated

but their relative proportion of the turbulent fluxes is correct.

### 2.3. Sapflow measurements

Sapflow stem gauges (Dynagage SGA5-WS Micro-sensors, Dynamax, Inc., Houston, TX) were deployed on eight soybean plants on 30 June (day 182) when soybean was at the V6 growth stage (Ritchie et al., 1994) and operated until 19 September (day 263). The gauges were connected to a Campbell Scientific CR10X data logger that output data every 15 min. Plants were selected that had uniform intrarow spacing and exhibited minimum cotyledon damage during emergence. Unifoliate and the first trifoliate petioles were removed in order to attach the stem gauges at least 0.15 m from the soil surface. All gauges were moved twice during the measurement period and were located within a 2 m<sup>2</sup> area. Average stem diameter measured on 6 and 19 August was 6.1 mm. Thermal conductivity of the stem was assumed to be 0.54 W m<sup>-1</sup> K<sup>-1</sup>. All gauges were covered with foam insulation and aluminum foil to minimize temperature gradients. Data from only six or seven plants were used due to gauge malfunction.  $T$  was calculated by multiplying the mean sapflow value by the plant density (Gerdes et al., 1994) and converted to a depth of water per 15 min interval.  $E$  (mm) was calculated as the difference between the eddy covariance LE (converted to ET) and sapflow stem gauge  $T$ .

### 2.4. $E$ and $T$ prediction

Energy balance approaches to the prediction of  $E$  and  $T$  in row crop environments, especially with incomplete cover, have been in use since Ritchie (1972). Morgan et al. (2003) predicted energy-limited evaporation from the soil ( $PTE_{\max}$ , W m<sup>-2</sup>) beneath a corn canopy in Wisconsin using a modified Priestley–Taylor (1972) equation

$$PTE_{\max} = \alpha_E \tau \left( \frac{s}{s + \gamma} \right) (R_n - G_0) \quad (3)$$

where  $\tau = R_{n,T}/R_n$ ,  $s$  the slope of the saturation vapor pressure versus temperature curve (kPa °C<sup>-1</sup>), and  $\gamma$  is the psychrometric constant (kPa °C<sup>-1</sup>). The Priestley–Taylor coefficient ( $\alpha_E$ ) was assumed = 1.3 when the soil was bare and to approach unity under full canopy conditions (Tanner and Jury, 1976), i.e.:

$$\alpha_E = 1 \quad (\tau \leq \tau_c) \quad (4)$$

$$\alpha_E = \alpha - \left[ \frac{(\alpha - 1)(1 - \tau)}{(1 - \tau_c)} \right] \quad (\tau > \tau_c) \quad (5)$$

where  $\tau_c$  is the constant value at which the LAI is sufficient for  $\alpha_E$  to reach unity. Tanner and Jury (1976) noted that  $\alpha_E$  should decrease under a canopy as the LAI increase and  $\tau$  decreases as the canopy acts to decrease the wind speed and increase the saturation deficit near the soil surface. Morgan et al. (2003) assumed a value of  $\tau_c = 0.55$ , which was also used in this study. Potential  $T$  ( $PTT_{\text{pot}}$ , W m<sup>-2</sup>) was also calculated using the Priestley–Taylor approach as

$$PTT_{\text{pot}} = \alpha \left( \frac{s}{s + \gamma} \right) (R_n - R_{n,T}) \quad (6)$$

with  $\alpha = 1.3$  and where  $R_n - R_{n,T}$  represents the net radiation intercepted by the canopy.

## 3. Results and discussion

Rainfall at the field site from June to September totaled 399 mm, which compares with the 30-year normal of 416 mm for these months (Owenby and Ezell, 1992). The precipitation was well distributed resulting in only one period (days 200–213) with surface soil water content below 0.2 (Fig. 1). Plant water stress was never observed during the measurement period. Plant height and LAI measurements commenced on days 162 and 182, respectively. Both canopy parameters increased rapidly from approximately days 190 to 220 with maximum canopy height of 0.99 m on day 225 and a maximum LAI of 5.85 on day 226 (Fig. 2). The difference between LAI 0.15 m above the soil surface and LAI measured at the soil surface averaged 0.37 and LAI at both heights closely followed quadratic curves with  $R^2 > 0.93$ .

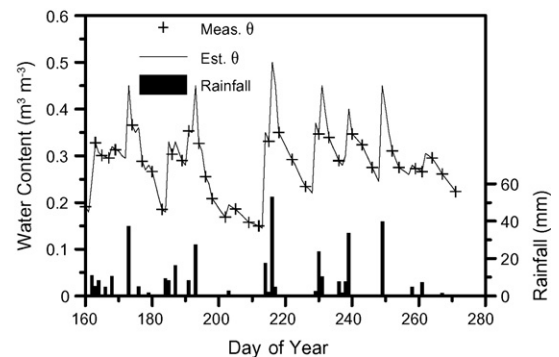


Fig. 1. Measured (+) and estimated (—) daily volumetric water content ( $\theta$ ) for the surface 0.06 m of soil and rainfall at the field site.

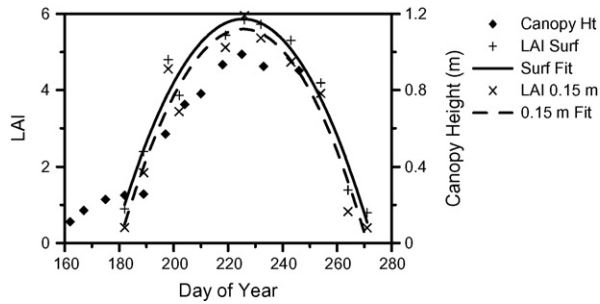


Fig. 2. LAI measured at the soil surface (+) and 0.15 m above the soil surface (x) with fitted curves and plant canopy height (♦) at the field site.

Mostly sunny days with wet soil conditions were screened for detailed analysis of the radiation components and ET partitioning. Thirteen days were identified that fit these criteria and provided a range of canopy conditions (developing, full, and senesced) and four representative days were selected for presentation (Fig. 3). On day 186 with a developing canopy, 78% of  $R_s$  was transmitted through the canopy under daytime conditions (defined as  $R_n > 100 \text{ W m}^{-2}$ ). Note that at this early date 23% of the LAI was below 0.15 m

(sensor height) therefore the intercepted shortwave is an underestimate. By contrast only ~12% of the daytime  $R_s$  was transmitted under full canopy conditions on days 219 and 245. This percentage increased to 40% on day 263 when the canopy had lost most of its leaves but still had an LAI of 2.25. Although longwave components above and below the canopy all varied between 300 and  $500 \text{ W m}^{-2}$ , under full canopy conditions the net longwave radiation above and below the canopy were generally  $<100$  and  $50 \text{ W m}^{-2}$ , respectively. Note that  $R_{l,\downarrow T}$ , which was calculated as the residual of the canopy radiation balance, exhibited the greatest amount of variation, especially during daytime hours. Curves of  $R_n$  above and below the canopy were very similar to the shortwave curves but with magnitudes reduced by the difference between the downwelling and upwelling longwave radiation.

Temporal patterns of ET components and available energy above and below the canopy illustrate the effectiveness of the soybean canopy in transpiring water and intercepting radiation (Fig. 4). Under sparse canopy conditions on day 186 with a maximum of  $\sim 500 \text{ W m}^{-2}$  available energy above the canopy, 78% of the  $R_n - G_0$  was utilized as ET with  $T$  accounting for 65% of the ET.

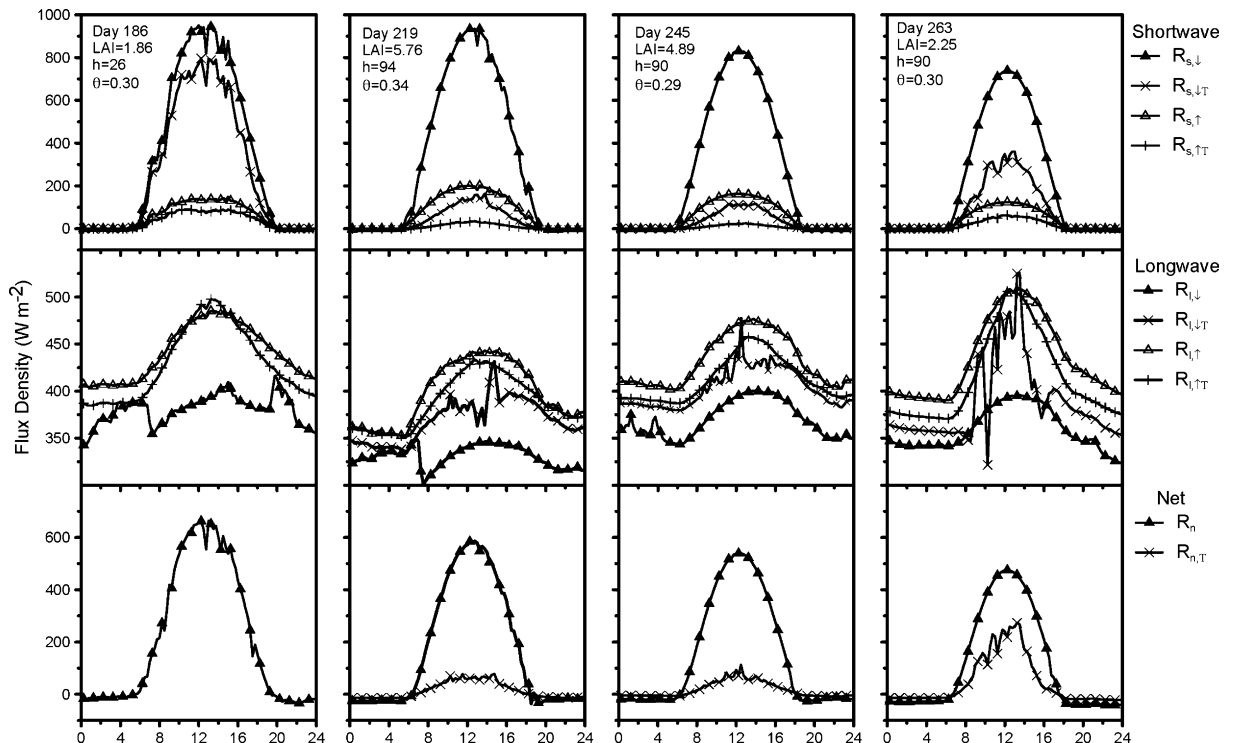


Fig. 3. Shortwave (top) and longwave (middle) components and net all-wave (bottom) radiation above and below the soybean canopy on four nearly cloud-free days. Subscripts denote waveband (s: shortwave, l: longwave, n: net all-wave), direction (↑: reflected or upwelling, ↓: incoming or downwelling), and whether transmitted through the canopy (T).



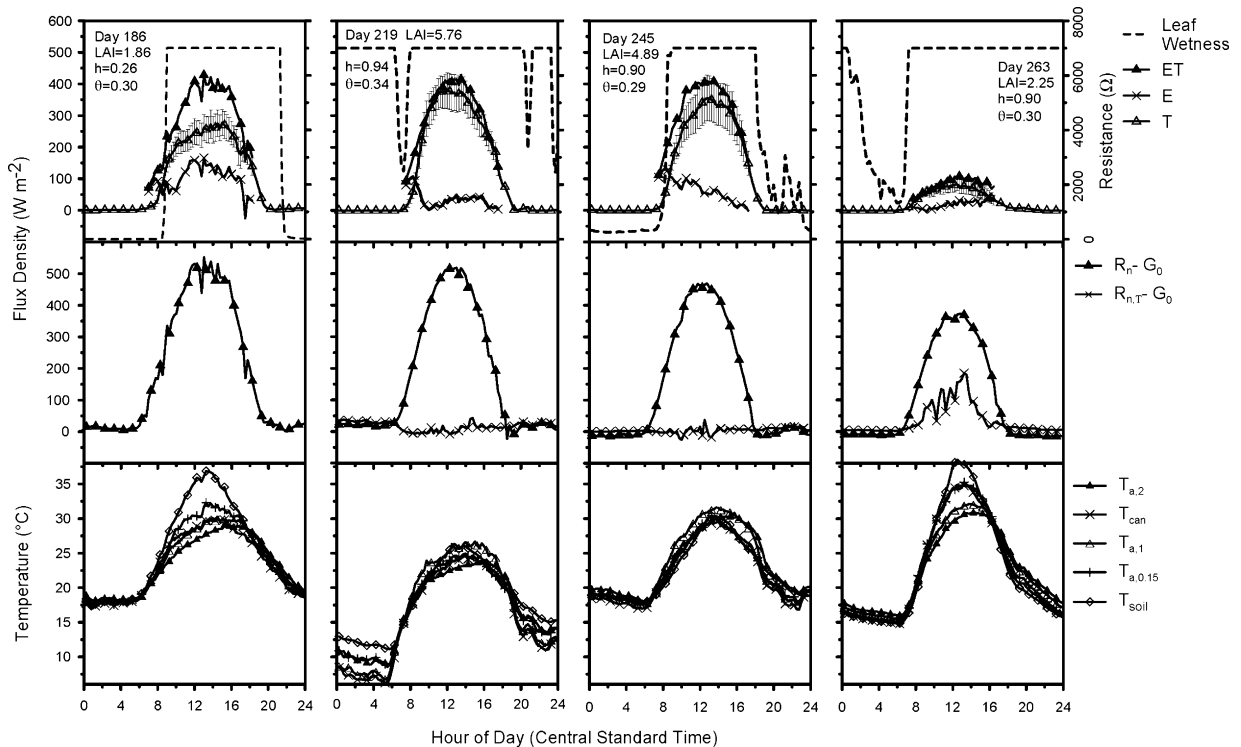


Fig. 4. Eddy covariance evapotranspiration (ET), sapflow stem gauge transpiration ( $T$ ), and leaf wetness (---) with estimated soil evaporation ( $E$ ) (top), available energy above ( $R_n - G_0$ ) and below ( $R_{n,T} - G_0$ ) the canopy (middle), and canopy ( $T_{can}$ ), air ( $T_{a,2}$ ,  $T_{a,1}$ ,  $T_{a,0.15}$ ), and soil surface ( $T_{soil}$ ) temperature (bottom) for the same days as Fig. 3. Error bars on  $T$  values represent one standard error from the mean of the sapflow stem gauges.

Of the 4.9 mm of ET on this day,  $T$  and  $E$  accounted for 3.2 and 1.7 mm, respectively. On days 219 and 245 with full canopy conditions, ET accounted for 83 and 97% of the available energy and  $T$  accounted for 88 and 92% of ET. There was 4.6 mm of ET on both days with  $E < 0.6$  mm. These values compare with values from Brun et al. (1972) who reported  $T$  accounted for 50% of the ET at an LAI of 2.0 and up to 95% at an LAI of 4 for a canopy with similar plant density but wider (0.6 m) row spacing. Sakuratani (1987), for a low-density canopy with 0.4 m row spacing, reported the  $T$  contribution to ET was 70% at an LAI of 2.0 and ~90% at the maximum LAI (3.0). On day 263 with a senesced canopy, only 30% of  $R_n - G_0$  was consumed by ET, which was the equivalent of 1.1 mm of evapotranspiration of which 1.0 was  $T$ . The large contribution of  $T$  to ET for a senesced canopy may be the result of desiccation of the standing stems as no transpiring leaves remained on the plants.

As  $E$  was calculated from the difference between ET and  $T$  measurements, the  $E$  estimate will include evaporation of any dew present on the plant canopy or soil. The leaf wetness sensor indicated the presence of dew (low resistance readings) on each of the 4 days with the greatest dew duration on days 186 and 245. Curves

of  $E$  under full canopy conditions just after sunrise show relatively high rates of evaporation that decreased with time during the day. It is likely, therefore, that some of the early morning  $E$  was actually evaporation of dew, not soil water evaporation (Sakuratani, 1987). Further evidence for this interpretation is the very low available energy beneath the canopy during the daytime on days 219 and 245, averaging only 6.6 and 2.2  $W m^{-2}$ , respectively, as compared to average  $E$  values of 36.8 and 23.8  $W m^{-2}$ . Clearly, available energy beneath the full soybean canopy was very limited and even the low  $E$  values obtained by the difference between ET and  $T$  may be overestimates of soil water evaporation.

Air, canopy, and soil temperature curves on day 219 and especially day 245 when ET accounted for 97% of the available energy display very small vertical temperature gradients across the soil–plant–atmosphere system (Fig. 4). Eddy covariance data indicated average daytime  $H$  on days 219 and 245 of only 66.4 and 20.6  $W m^{-2}$ , respectively. Wind speed was also very low on these days (maximum  $< 2.3 m s^{-1}$ ), which would also inhibit sensible heat transfer between the canopy and atmosphere. The very high proportion of energy consumed as LE (97%) on day 245 may also

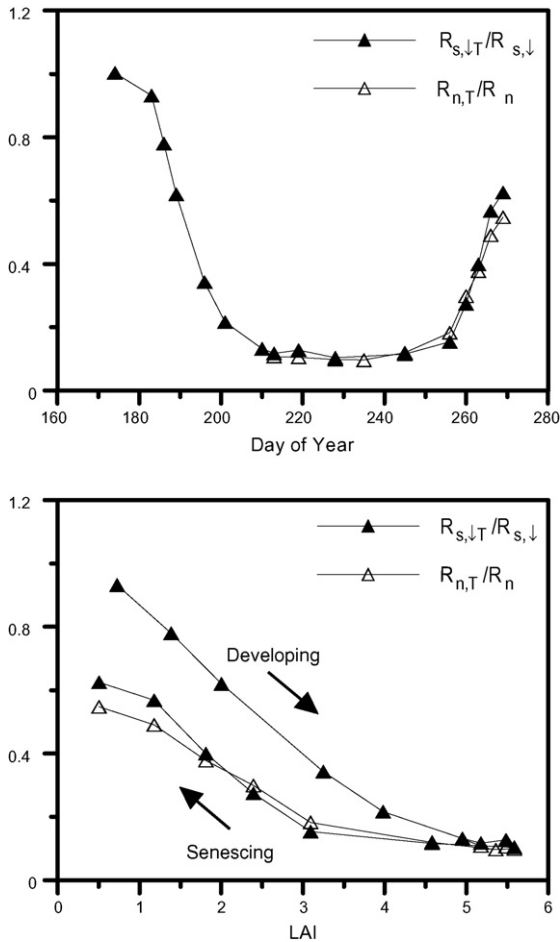


Fig. 5. Ratio of above-canopy to below-canopy incoming solar ( $R_{s,\downarrow T}/R_{s,\downarrow}$ ) and net all-wave ( $R_{n,T}/R_n$ ) radiation on sunny days by day of year (top) and by LAI (bottom). All below-canopy measurements were at 0.15 m above the soil surface.

have been influenced by large scale air movements as  $H$  was negative after 3 p.m. and  $T_{a,2}$  was 2–3 °C warmer than  $T_{can}$ . These conditions suggest advective energy inputs in the late afternoon, which would supply

additional energy for ET. Under sparse and senesced canopy conditions, significant (5–10 °C) warming of the soil and near-surface air occurred during the daytime with much larger average  $H$  values of 82.3 and 201.5  $W\ m^{-2}$ , respectively.

On mostly sunny days during the growing season, patterns of daytime average values of  $R_{n,T}/R_n$  closely followed  $R_{s,\downarrow T}/R_{s,\downarrow}$  (Fig. 5). Variation of  $R_{s,\downarrow T}/R_{s,\downarrow}$  with LAI exhibited consistently lower values during canopy senescence ( $\sim 0.2$  lower) than for the same LAI during canopy development. This result can be attributed to differences in radiation interception between a short, growing canopy with many green leaves versus a tall canopy that is losing leaves until it is composed only of senesced stems and pods. There were also much greater solar zenith angles near the end of the growing season (19.2° on day 178 versus 44.0° on day 271). Extinction coefficients for  $R_n$  and all  $R_{s,\downarrow}$  data from sunny days were 0.439 and 0.414, respectively, with  $R^2$  of 0.91 and 0.88. When the  $R_{s,\downarrow}$  data were divided into growing and senescing phases, the extinction coefficients were 0.385 and 0.518 with  $R^2$  of 0.95 and 0.93.

Days 219 and 245 were selected to test the accuracy of Eqs. (3) and (6) for estimating  $E$  and  $T$  under energy-limiting conditions (Fig. 6). Significant rainfall had occurred prior to these days (58 mm on days 216 and 217, 33.5 mm on day 239). Daytime  $T$  predicted with Eq. (6) ( $PTT_{pot}$ ) was 5.1 mm compared to the measured  $T$  of 4.1 mm on day 219. A better result was found on day 245 with  $PTT_{pot} = 4.8$  mm and  $T = 4.6$  mm. Daytime  $E$  predicted with Eq. (3) ( $PTE_{max}$ ) was 0.44 mm on days 219 and 0.47 mm on day 245 compared to measured  $E$  values of 0.56 and 0.35, respectively. The energy balance approach produced  $T$  estimates that were 25 and 14% greater than the measured  $T$  and  $E$  estimates that were 21% less than and 35% greater than the measured  $E$ . An  $E$  underestimate, especially in the early morning, may be explained by the  $E$  data

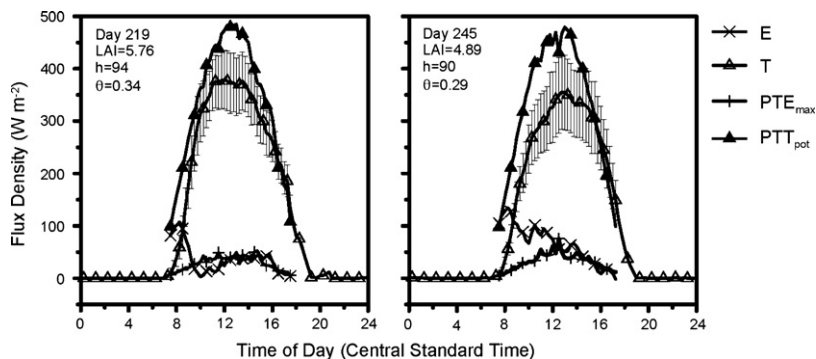


Fig. 6. Estimated soil water evaporation ( $E$ ) and sapflow stem gauge transpiration ( $T$ ) with predicted maximum  $E$  ( $PTE_{max}$ ) and potential  $T$  ( $PTT_{pot}$ ) for days 219 and 245. Error bars on  $T$  represent one standard error from the mean of the sapflow stem gauges.

including the evaporation of dew. Nocturnal dewfall on the order of 0.1–0.5 mm has been reported in temperate regions (Wallin, 1967), which is within the range of the observed differences between  $PTE_{\max}$  and  $E$  (+0.12 mm on day 219 and –0.12 mm on day 245). Another potential source of error is the plant-to-plant variation in sap flow. Average daytime standard errors for  $T$  on days 219 and 245 were 42.2 and 49.0 W m<sup>-2</sup> (0.016 and 0.019 mm), respectively.

Previous applications of the energy balance approach for partitioning ET (Tanner and Jury, 1976; Morgan et al., 2003) utilized above-canopy measurements and radiation extinction coefficients to estimate  $R_n$  interception by the canopy as direct measurement of  $R_{n,T}$  is rare. Direct measurement of  $R_n$  and  $R_{n,T}$  in this study did not appear to improve the prediction of  $T$ , likely due to the close similarity in canopy attenuation of shortwave and net radiation as illustrated in Fig. 5.  $PTT_{\text{pot}}$  calculations were repeated using measured  $R_n$  with  $R_{s,\downarrow}$  extinction coefficients using all data and growing, and senescing phases separately to estimate intercepted  $R_n$ , but the  $PTT_{\text{pot}}$  values changed <6%. Another possible explanation for the discrepancy between  $PTT_{\text{pot}}$  and  $T$  is that transpiration was water-limited. This seems unlikely on day 219 with significant rainfall two days earlier, the canopy was near its peak LAI, and average daytime air temperature of 21.6 °C and vapor pressure deficit of 1.04 kPa. It may have been a possibility on day 245 as the most recent rainfall was 33.5 mm on day 239 and the canopy had started to senesce, however, abscission of lower leaves has minimal effect on  $T$  as both Sakamoto and Shaw (1967) and Hatfield and Carlson (1978) found ~90% of light capture in soybean canopies occurs in the top leaves of the canopy.

#### 4. Conclusions

Recent trends in soybean production practices including more narrow rows and high plant populations have created very dense plant canopies with commensurate microclimate characteristics. Radiation and ET measurements in a 0.38 m row canopy with 350,000 plants ha<sup>-1</sup> throughout the growing season indicate that a very dense canopy develops with an LAI exceeding 5.5. On sunny days under full canopy conditions, nearly 90% of the shortwave and net radiation was attenuated by the canopy and over 80% of the available energy utilized by ET.  $E$  accounted for only 8–12% of the ET under full canopy conditions although these percentages may be overestimates due to evaporation of dew present in the canopy. With such a large proportion of the available energy consumed by

ET, fluxes of  $H$  were very low and vertical temperature gradients across the soil–canopy–atmosphere interface were only 2–3 °C.

A Priestley–Taylor energy balance approach used to estimate  $E$  and  $T$  tended to underestimate  $E$  and overestimate  $T$ . The  $E$  underestimate may be due in part to  $E$  including evaporation of dew present on the canopy. Conversely,  $T$  was overestimated by 25 and 14% on sunny days under full canopy conditions even with direct measurement of  $R_n$  interception by the canopy. Use of the standard method of extinction coefficients to estimate  $R_n$  interception failed to improve  $T$  estimates significantly. Further effort will be necessary to discern the cause for this discrepancy and will be needed if more accurate simulation of ET partitioning is to be achieved by this energy balance approach. The high-population, narrow-row planting strategy resulted in a dense canopy that, under full canopy conditions, allowed very little light penetration or soil water evaporation.

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